A Novel Resonant LLC Soft-Switching Buck Converter

Masoud Jabbari
Electrical Engineering Department, Najafabad Branch,
Islamic Azad University
Isfahan, Iran
Masuod.jabbari@gmail.com

Habib Kazemi
Electrical Engineering Department, Najafabad Branch,
Islamic Azad University
Isfahan, Iran
Habib_kazemii@yahoo.com

Nahid hematian
Electrical Engineering Department, Najafabad Branch,
Islamic Azad University
Isfahan, Iran
Mrshematian@yahoo.com

Ghazanfar Shahgholian
Electrical Engineering Department, Najafabad Branch,
Islamic Azad University
Isfahan, Iran
Shahgholian@iaun.ac.ir

Abstract—a new LLC resonant DC–DC buck converter is presented. The employed multi-resonant tank provides soft-switching conditions for all semiconductor devices independent from the operating voltages and the load current. The proposed converter enjoys useful advantages such as low element count, unconditional soft switching operation, self short-circuit protection, high efficiency and low EMI. Circuit analysis and important relations are presented in this paper. Experimental results from a 60W laboratory prototype confirm the presented theoretical analysis.

Keywords —buck converter; soft-switching; DC-DC converter; ZCS; power supply.

I. INTRODUCTION

Soft-switching converters have been widely employed for DC-DC power conversion because at soft-switching conditions, switching losses and electromagnetic interference (EMI) are reduced. Moreover, switching frequency can be increased to enhance the converter power density. This condition is commonly attained by zero-voltage switching (ZVS) or zero current-switching (ZCS) [1]-[15].

Resonant converters are a family of soft-switching converters in which energy is transferred through a high frequency resonant tank, and switching is performed at zero-crossing instants of the switches current or voltage. A series resonant LC tank is the simplest network which is employed in the resonant converters to provide ZCS [1]-[8]. The main advantage of this converter (series resonant converter, SRC) is major size reduction of the passive components. Further resonant networks such as LLC, LCC, etc. are also proposed however the number of elements is increased and the system possesses complicated characteristics [11]-[15]. As a non-isolated converter, a restriction of the conventional resonant converters is the requirement of a full-wave rectifier which detaches the common ground of the load and source. This is in addition to the increased number of elements and conduction losses.

A new family of resonant converters so-called switched-resonator converters is proposed in [8]. Based on the mentioned general scheme in [8], this paper presents a new resonant step-down converter shown in Fig. 1. In this converter, passive components include a high frequency resonant LLC tank and a filtering capacitor at the output. ZCS condition is achieved at both turn-on and turn-off switching instants independent of the load-current and operating voltages. Comparing with the HB-SRC, not only the proposed converter has three power diodes less, which results in lower conduction losses and lower price, but also it is suitable for non-isolated applications. Moreover, the inductor placed in series with Q1 and Q2 inhibits creation of spiky current produced in the conventional bridge arms due to the severe reverse recovery problem of the switches anti-parallel diodes. Experimental results from a 60W/150kHz prototype verify the integrity of operation and the presented theoretical analysis.

II. BUCK CONVERTER ANALYSIS

The proposed buck converter showing in Fig. 1 consists of two switches (Q1, Q2), a resonant LLC network (Lr1, Lr2, and Cr), the rectifying diode (D), and the output filtering capacitor (C). The converter has five operating modes as illustrated in Fig. 2. To simplify, it is assumed the converter is in steady state, all switching devices and passive elements are ideal, and the output capacitor C is large enough such that the output voltage is constant during one switching cycle.

Fig. 1 Proposed buck converter
The following quantities are defined.  

\[ L_r = L_{r1} + L_{r2}, \quad \alpha = \frac{L_{r2}}{L_r} \]  

\[ \omega_r = \frac{1}{\sqrt{L_1 C_1}}, \quad f_r = \frac{1}{2\pi \sqrt{L_r C_r}} \]  

\[ Z_r = \frac{L_r}{C_r}, \quad r = \frac{R}{Z_r}, \quad A = \frac{V_o}{V_s} \]

\[ V_c(t) = \frac{V_r(t)}{V_s}, \quad I_{r2}(t) = \frac{i_{r2}(t)}{V_s / Z_r} \]  

Figs. 3 shows the steady-state waveforms. The initial currents of all inductors are zero and the initial voltage of the resonant capacitor \( C_r \) is \( V_r = 2V_o \). The operating modes are as follows.

**Mode I (t_0-t_1)**

Prior to \( t_0 \), the current of \( L_{r1} \) is zero, then \( Q_1 \) is turned on at \( t_0 \) under the ZCS condition and \( C_r \) charges through a resonance with \( L_{r1} \) and \( L_{r2} \) up to \( 2V_s - 2V_o \). At the end of this mode, the current of \( Q_1 \) reaches zero and therefore this switch is turned off at ZCS.

\[ I_c(t) = (1 - 2A) \sin(\omega_c(t - t_0)) \]  

\[ V_r(t) = 1 - (1 - 2A) \cos(\omega_c(t - t_1)) \]  

\[ t_1 - t_0 = \sqrt{\alpha} \frac{T_c}{2} \]  

\[ V_c(t_1) = 2(1 - A) \]  

\[ I_{r2}(t_1) = 0 \]

**Mode II (t_1-t_2)**

At \( t_1 \), \( Q_2 \) is turned on at ZCS and a resonance starts between \( C_r \) and \( L_{r2} \) which discharges \( C_r \) through \( L_{r2} \) and delivers power to the output. At \( t_2 \) the resonance voltage \( v_r \) reaches zero.

\[ I_{r2}(t) = \frac{(A - 2)}{\sqrt{\alpha}} \sin\left(\frac{\omega_r}{\sqrt{\alpha}}(t - t_1)\right) \]  

\[ V_r(t) = -A + (2 - A) \cos\left(\frac{\omega_r}{\sqrt{\alpha}}(t - t_1)\right) \]  

\[ t_2 - t_1 = \frac{\sqrt{\alpha}}{\omega_r} \left[ \pi - \cos^{-1}\left(\frac{A}{A - 2}\right) \right] \]

**Mode III (t_2-t_3)**

By reaching \( v_r \) to zero at \( t_2 \) the diode \( D_r \) is forward biased at ZVS and the stored magnetic energy in \( L_{r2} \) is delivered to the output during this mode. By reaching \( i_{r2} \) to zero at \( t_3 \), the switch \( Q_2 \) and the diode \( D_r \) are both turned off at ZVZCS. During this mode, \( v_r \) stays constant at zero.

\[ I_{r2}(t) = I_r(t) + \frac{A \omega_r}{\alpha}(t_3 - t_2) \]

\[ V_r(t_3) = 0 \]

**Mode IV (t_3-t_4)**

At \( t_3 \), \( Q_1 \) is turned on at ZCS and a resonance starts between \( L_{r1} \) and \( L_{r2} \) which discharges \( L_{r1} \) through \( L_{r2} \) and delivers power to the output. At \( t_4 \) the resonance voltage \( v_r \) reaches zero.

\[ I_{r2}(t) = \frac{A}{\sqrt{\alpha}} \sin\left(\frac{\omega_r}{\sqrt{\alpha}}(t - t_3)\right) \]  

\[ V_r(t) = -A + (2 - A) \cos\left(\frac{\omega_r}{\sqrt{\alpha}}(t - t_3)\right) \]  

**Mode V (t_4-t_5)**

At \( t_4 \), \( Q_1 \) is turned on at ZCS and a resonance starts between \( L_{r1} \) and \( L_{r2} \) which discharges \( L_{r1} \) through \( L_{r2} \) and delivers power to the output. At \( t_5 \) the resonance voltage \( v_r \) reaches zero.
Mode IV (t3-t4)

At t3, the anti-parallel diode of Q2 (d2), is forward biased at ZVS and then the voltage polarity of Cr reverses via a resonance with Lr2. At t4, the resonance voltage vr reaches 2Vo and d2 is turned off at ZCS.

\[ I_{r2}(t) = \frac{A}{\sqrt{\alpha}} \sin \left( \frac{\alpha}{\sqrt{\alpha}} (t-t_3) \right) \]  
(19)

\[ V_r(t) = A - A \cos \left( \frac{\alpha}{\sqrt{\alpha}} (t-t_3) \right) \]  
(20)

\[ t_4 - t_3 = \frac{\sqrt{\alpha} T_r}{2} \]  
(21)

\[ V_r(t_4) = 2V_o \]  
(22)

\[ I_{r2}(t_4) = 0 \]  
(23)

Mode V (t4-t5)

During this mode, all semiconductor devices are off and the load is supplied by the output capacitor (dead time). By controlling the duration of this mode, the converter voltage gain is determined.

At steady state, the converter voltage gain can be calculated by satisfying the energy conservation principle as (24). By substituting (5) in (24) and simplifying, (25) is obtained in which \( f_s = 1/T_s \) is the switching frequency and \( f_r \) is the resonant frequency.

\[ \int_{t_4} V_{iT} dt = \frac{V_o^2}{R} T_s \]  
(24)

\[ S = \frac{r}{\pi} f_s = \frac{A^2}{1-2A} \]  
(25)

In absence of dead-time (Mode V), the switching frequency is at maximum and thus maximum voltage gain is also attained which is defined by \( A_m \). The minimum switching period is defined as \( T_m \) which is obtained as (26). By substituting \( f_s = T_m^{-1} \) in (24), (27) is attained, wherein, in fact, \( A_m \) is a function of \( r \). This equation is required for converter design. For \( \alpha = 0 \) and \( \alpha = 1 \), \( A_m \) against \( r/\pi \) is sketched in Fig. 4.

\[ \frac{T_m}{T_r} = \frac{1}{2} + \frac{\sqrt{\alpha} + \sqrt{\alpha} \pi}{\pi} \left[ \sqrt{1-A} - \frac{1}{2} \cos^{-1} \frac{A}{A-2} \right] \]  
(26)

\[ r = \frac{A_m^2}{1-2A_m} \left[ \frac{\pi}{2} + \pi \sqrt{1-A_m} \left( A_m - \frac{\sqrt{A_m} \cos^2 \frac{A_m}{2}}{A_m-2} \right) \right] \]  
(27)

At output short circuited, \( A \) is zero and thus according to (26) \( T_m \) goes infinity. Since \( T_m \) is the shortest switching period, power transferring is automatically stopped when the output is short-circuited (self short-circuit protection).

![Fig. 3 Steady-state key waveforms](image)

![Fig. 4 Maximum attainable voltage gain against r/π](image)
IV. DESIGN PROCEDURE

The parameter $\alpha$ can be used as one degree of freedom for attaining the maximum of efficiency. Consider a 60W prototype converter with the following specifications:

1. Input voltage, $V_s=155\text{V} \pm 10\%\text{V}$
2. Output voltage, $V_o =48\text{V} \pm 1\%$
3. Resonant frequency, $F_r=150\text{kHz}$
4. And with 20% overdesign

**Step 1- Determining $\alpha$:** The curve of efficiency versus $\alpha$ is sketched in Fig.5. This figure is the result of simulation with Pspice software. According to this figure, by choosing $\alpha=0.8$ the efficiency is set at maximum.

**Step 2- Determining $Z_r$:** $r$ is obtained by substituting $A_m=48/ (155\times 0.9)$ in (27), then according to (3), $r=1.52$ is obtained where $R=V_o^2/P_{out,max}$ is the load resistance. By applying 20% overdesign $Z_r= 23.2\Omega$ is obtained. Then, $C_r=46\text{nF}$, $L_{r_1}= 4.9\text{\mu H}$, $L_{r_2}= 19.6\text{\mu H}$ are calculated.

**Step 3-** The resonant tank characteristics angular frequency $\omega_r$ determines switching frequency and should be ascertained by considering the technology of the employed switches.

V. EXPERIMENTAL RESULTS

A prototype of the proposed buck converter is implemented, and the waveforms are presented to verify the theoretical analysis. Input and output voltages are 155V and 48V, respectively. The main and auxiliary switches are IRF640 (200V, $R_{DS(on)}=0.18\Omega$), diode is MUR840 (400V) and the output capacitor is 100\text{uF}. The passive elements are $C_r=46\text{nF}$, $L_{r_1}= 4.9\text{\mu H}$, $L_{r_2}= 19.6\text{\mu H}$. Both inductor cores are ferrite type, and the resonant capacitor is MKP type (metalized polyethylene). The waveforms of $Q_1$ and $Q_2$ are presented in Fig. 6. All semiconductor devices operate under soft-switching condition (TABLE I). A guard-time equal to 400ns exists between $Q_1$ turn-off and $Q_2$ turn-on. The converter efficiency is measured greater than 94%.

<table>
<thead>
<tr>
<th>Mode</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_1$</td>
<td>Turn on-ZCS</td>
<td>Turn off-ZCS</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>$Q_2$</td>
<td>OFF</td>
<td>Turn on-ZCS</td>
<td>ON</td>
<td>Turn off-ZVS</td>
<td>OFF</td>
</tr>
<tr>
<td>$D_r$</td>
<td>OFF</td>
<td>OFF</td>
<td>Turn on-ZVS</td>
<td>Turn off-ZVS</td>
<td>OFF</td>
</tr>
</tbody>
</table>

VI. CONCLUSIONS

A new LLC resonant buck converter is presented. In the proposed converter, the input and output terminals possess common ground and all semiconductor devices, operate under soft-switching condition which result in increase of efficiency and power density and decrease of EMI. Modal analysis, important equations and design procedure are presented. Experimental results from a 60W laboratory prototype verify the proposed converter operation.

![Fig. 6 Practical Results, respectively from the top: $V_{G_S}$ of $Q_1$ (5V/div), $V_{G_S}$ of $Q_2$ (5V/div), $V_{C_S}$ of $Q_1$ (50V/div), $V_{C_S}$ of $Q_2$ (50V/div), $I_{q_1}$ (200mA/div), $I_{r}$ (200mA/div), $L_1$ (200mA/div) and $V_r$ (50V/div). Time scale=5\mu s/div](image)
Fig. 7 Implemented converter

REFERENCES


